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Application of Analytical Heat Transfer Models of Multi-layered Natural and Engineered Barriers to Compare Alternatives for High-Level Nuclear Waste (HLW) Disposal

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Abstract

A combination of transient heat transfer analytical solutions for a finite line source, a series of point sources, and a series of parallel infinite line sources were combined with a quasi-steady-state multi-layered cylindrical solution to simulate the temperature response of a deep geologic radioactive waste repository with multi-layered natural and engineered barriers.

This evaluation was performed to provide information to scientists and decision makers to facilitate the selection of a potential site suitable for a repository, and to provide input for the future evaluation of the trade-off between pre-emplacement surface storage time and repository footprint.

This approach was used instead of the typical finite element solution used to analyze the temperature response because it allowed rapid comparison of a large number of alternative disposal options and design configurations. More than 100 combinations of waste form, geologic environment, repository design configuration, and surface storage times were analyzed and compared in a few weeks time.

The Used Fuel Disposition (UFD) Campaign within the Department of Energy's Office of Nuclear Energy (DOE-NE) Fuel Cycle Technology (FCT) program has been tasked with investigating the disposal of the nation's high-level nuclear waste (HLW) and spent nuclear fuel (SNF) from commercial nuclear power plants, in a range of potential waste forms and geologic environments.

For each waste form and geologic environment combination, there are multiple options for a repository conceptual design, and computation times for comparison of alternatives using finite-element computer codes can make parametric sensitivity studies expensive and time consuming. An alternate approach using two analytical heat transfer solutions was developed. One modeled the transient in the host rock outside of the waste emplacement borehole or tunnel, assuming a homogeneous infinite medium. A second model of the Engineered Barrier System (EBS) components, inside the waste emplacement borehole or tunnel, applied a quasi-steady-state multi-layer cylindrical solution. The model development is documented in Sutton et al 2011a and 2011b.

The "outside" model calculates a temperature transient given decay heat data from the waste form, at the borehole or tunnel wall of a geologic repository by assuming the uniform infinite medium extends both inside and outside the "calculation radius".

The "inside" model uses the temperature calculated by the "outside" model at the host rock wall surface in conjunction with the transient heat source, and calculates the thermal gradient through the EBS using a steady-state multi-layer cylindrical model solution.

This approach is reasonable because the thermal mass of the EBS components is much smaller than the infinite mass of host rock surrounding the EBS. There is a short (on the order of weeks or months) transient in the EBS components when the waste is initially placed in the repository. After that the components appear to be effectively at a steady state temperature with respect to the continuing temperature transient in the surrounding host rock, which slowly evolves because of its large thermal mass.

These models allowed thermal performance comparisons to address alternative disposal concepts including

- Four host rock environments – crystalline rock (granite), clay, salt, and deep borehole
- Three potential advanced nuclear fuel cycle concepts
    - Once through high-burnup uranium oxide (UOX) Light Water Reactor (LWR) fuels
    - Modified open cycle including mixed oxide fuels (MOX) and high-level waste glass (Co-extraction)
    - A full recycle concept based on an Advanced Burner Reactor (ABR) with three types of high-level waste (New-extraction HLW glass, electro-chemical ceramic HLW, and electro-chemical metal HLW)
- Two different EBS design concepts in each media, one for used nuclear fuel assemblies (SNF), and one for HLW canisters
- Four different surface storage assumptions – 10, 50, 100, and 200 years
- Five different SNF waste package assembly capacities – 1, 2, 3, 4, and 12 assemblies (evaluated for the once-through and modified-open fuel cycles)

Workshop to Define Candidate Repository Design Concepts in Various Media

Lawrence Livermore National Laboratory (LLNL) hosted a 2-day workshop on thermal load and repository concepts in June 2011, with participation from Sandia National Laboratory (SNL), Oak Ridge National Laboratory (ORNL), and Savannah River National Laboratory (SRNL).

The team discussed, and selected basic input data to be analyzed for:

- Thermal load from a variety of waste streams,
- Repository configurations, and
- Material properties and thermal constraints

The repository configurations selected were based on current international design concepts for both SNF and HLW deep geologic disposal systems in each of the host rock types, and are documented in Hardin et al 2011. Design concepts were considered for the various media for

- Salt - from Germany and the US
- Clay – from Belgium, France, and Switzerland
- Granite (crystalline rock) – from Sweden and Finland
- Deep Borehole – from Sweden and the US

To model the wide variety of international design concepts a standardized EBS geometry was defined, such that each of the concepts modeled would use a subset of a generic layout of concentric EBS material layers.

The parametric sensitivity study enabled by this approach allowed us to gain insights with respect to required surface storage times, and waste package capacities needed to meet thermal constraints for various waste forms in each of the geologic media.

References:

Hardin et al 2011 - SAND2011-6202, Ernest Hardin (SNL); Jim Blink, Harris Greenberg, Mark Sutton and Massimiliano Fratoni (LLNL); Joe Carter and Mark DuPont (SRNL); and Rob Howard (ORNL), *Generic Repository Design Concepts and Thermal Analysis (FY11),* August 2011.

Sutton et al 2011a - LLNL-TR-491099 - Mark Sutton, James A. Blink, Massimiliano Fratoni, Harris R. Greenberg and Amber D. Ross, *Investigations On Repository Near-Field Thermal Modeling*, July, 2011

Sutton et al 2011b - LLNL-TR-484011- Mark Sutton, James A. Blink, Massimiliano Fratoni, Harris R. Greenberg, William G. Halsey and Thomas J. Wolery, *Disposal Systems Evaluation Framework Version 1.0 - Progress Report*, May 2011

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